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**Kitanaka**

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(54) **CONTROL APPARATUS FOR AC MOTOR**(56) **References Cited**

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*H02P 21/04* (2006.01)  
*H02P 21/05* (2006.01)

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***21/04*** (2013.01); ***H02P 21/05*** (2013.01); ***H02P***  
***27/08*** (2013.01); ***B60L 2240/421*** (2013.01);  
***B60L 2240/423*** (2013.01); ***B60L 2240/427***  
(2013.01); ***B60L 2240/429*** (2013.01); ***H02P***  
***2205/05*** (2013.01); ***Y02T 10/643*** (2013.01);  
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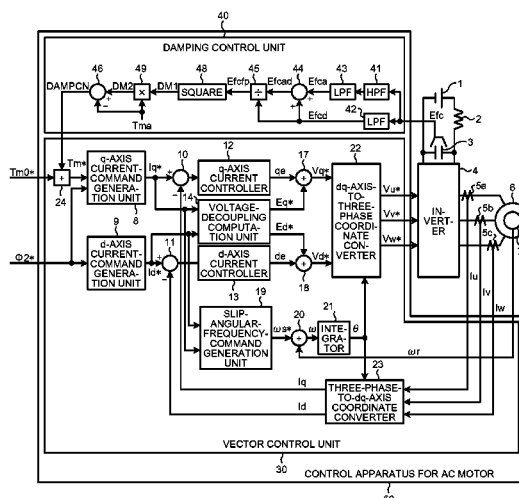
None

See application file for complete search history.

(57) **ABSTRACT**

A control apparatus for an AC motor that drives and controls the AC motor includes a damping control unit that calculates a damping manipulated variable that suppresses a fluctuation in the capacitor voltage, wherein the damping control unit calculates a fluctuation rate of the capacitor voltage, calculates the damping manipulated variable based on the fluctuation rate and a predetermined value that is set as a value in a predetermined range around a maximum torque of the AC motor, generates a torque command or a current command of the AC motor based on the damping manipulated variable, and controls an inverter so as to change a current flowing in the inverter in a fluctuation suppressing direction with respect to a fluctuation in the capacitor voltage based on the torque command or the current command.

**7 Claims, 4 Drawing Sheets**



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**B60L 15/02** (2006.01)

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FIG.1

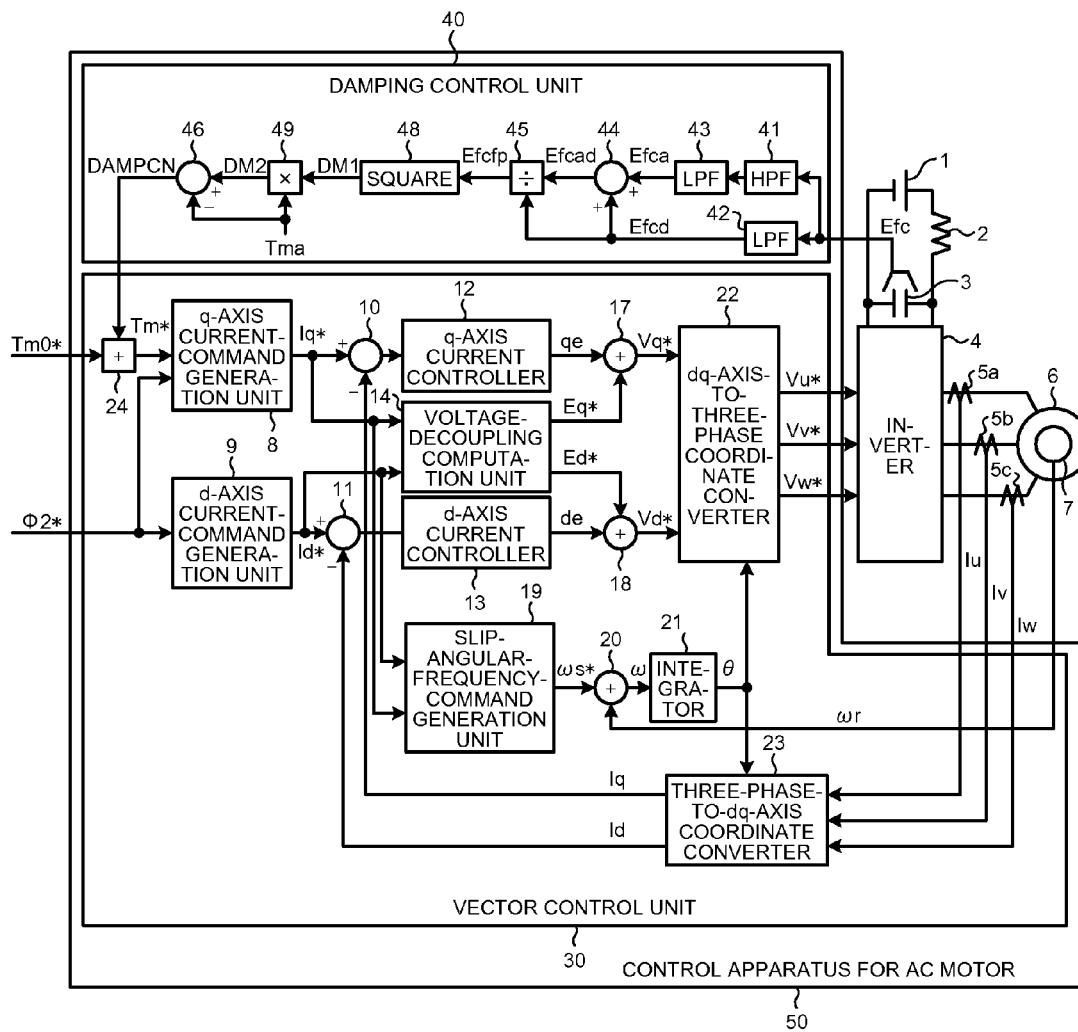


FIG.2

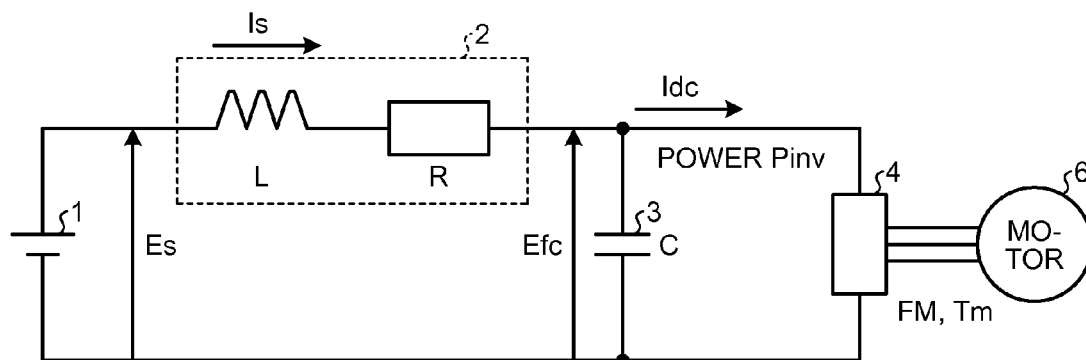


FIG.3

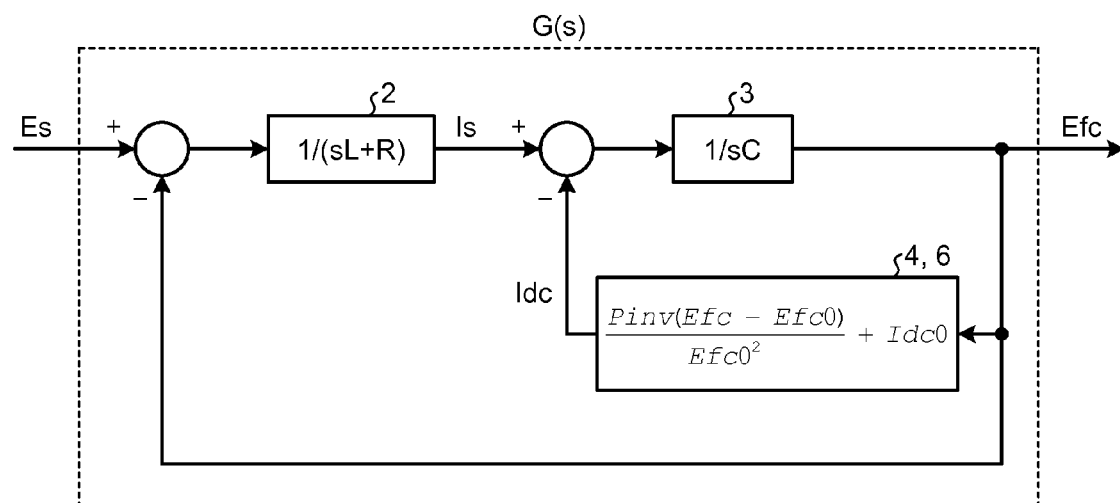


FIG.4

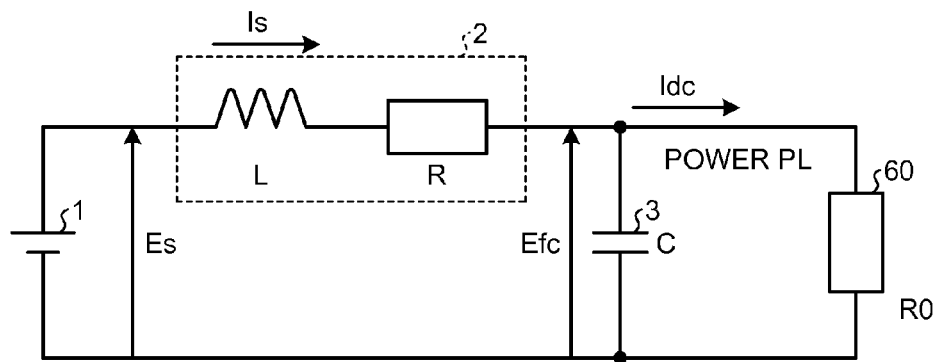


FIG.5

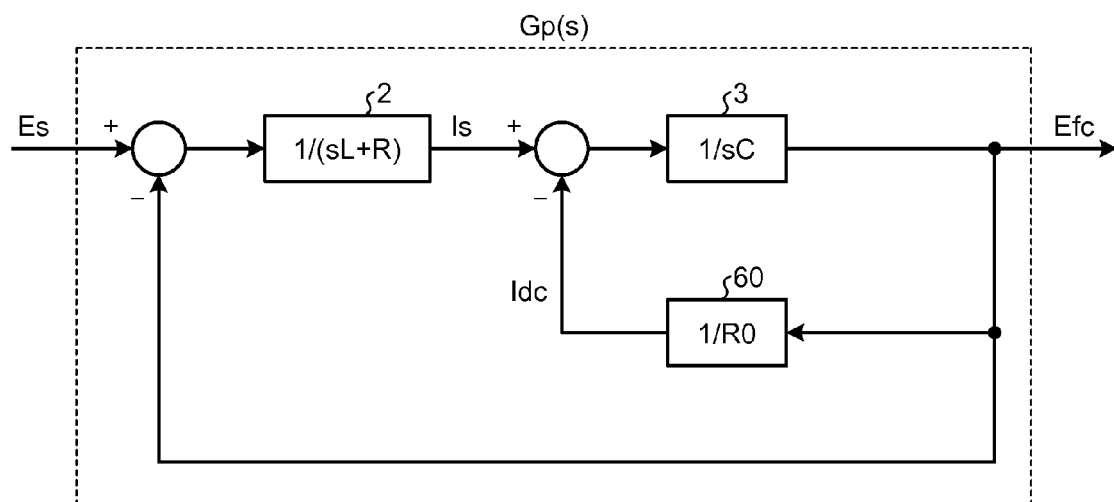
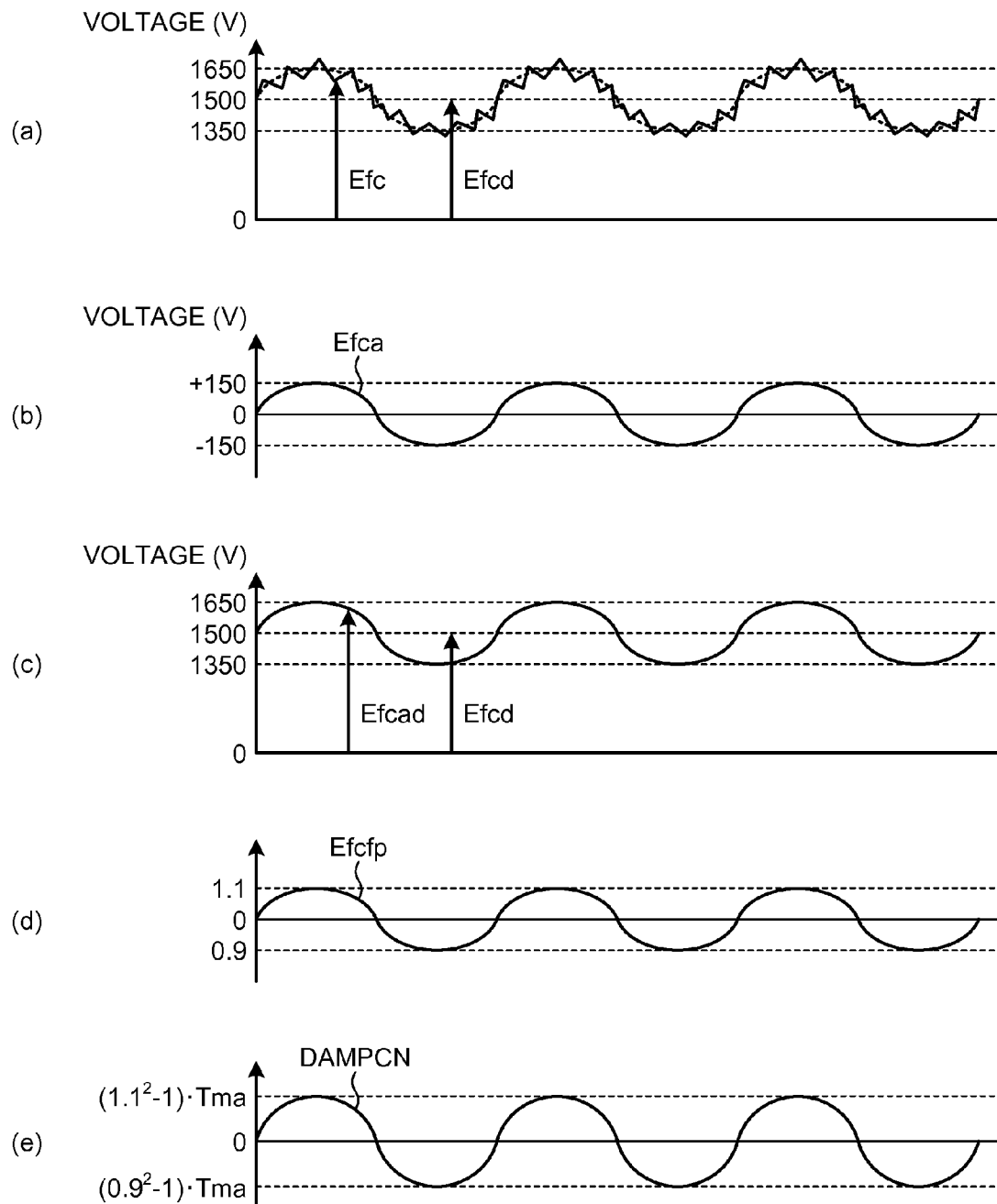


FIG.6



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**CONTROL APPARATUS FOR AC MOTOR****FIELD**

The present invention relates to a control apparatus for an AC motor for driving and controlling an AC motor.

**BACKGROUND**

A technique for driving and controlling an AC motor using an inverter has been widely used in the industrial field. The technique is conventionally and widely used also in electrical railroads. However, it is known that in a case of applying the above system to a DC feeding electrical railroad, electrical oscillation occurs in a harmonic-absorption LC filter circuit arranged on the DC side of an inverter and constituted by a reactor and a capacitor, and a voltage across the capacitor (a capacitor voltage) oscillates, which makes a control over the motor unstable. A damping control method for suppressing this oscillation is disclosed in Patent Literature 1 mentioned below.

Patent Literature 1 mentioned below discloses a configuration that controls an inverter to have a positive resistance characteristic with respect to a fluctuation amount of a capacitor voltage  $E_{fc}$  by configuring the control apparatus such that a torque command  $T_m^*$  is multiplied by a damping manipulated variable that is a value obtained by squaring a fluctuation rate of the capacitor voltage  $E_{fc}$  and suppresses the electrical oscillation of an LC filter circuit, thereby making a control over the motor stable.

**CITATION LIST****Patent Literature**

Patent Literature 1: Japanese Patent No. 4065901

**SUMMARY****Technical Problem**

However, with the above conventional technique, in order to change an inverter input power  $P_{inv}$  such that the inverter has a positive resistance characteristic, the torque command  $T_m^*$  is multiplied by the damping manipulated variable. Accordingly, when the torque command  $T_m^*$  is either zero or a small value close to zero, the damping manipulated variable becomes either zero or a small value close to zero, and it is impossible to change the inverter input power  $P_{inv}$ .

For example, when the torque command  $T_m^*$  is zero, there are problems that it is impossible to manipulate the inverter input power  $P_{inv}$  using a damping manipulated variable DAMPCN, and the apparatus cannot exhibit a sufficient performance for suppressing the oscillation of the capacitor voltage  $E_{fc}$  in a case where a disturbance such as a fluctuation in an overhead line voltage causes the oscillation of the capacitor voltage  $E_{fc}$ .

The present invention has been achieved to solve the above problems, and an object of the present invention is to provide a control apparatus for an AC motor capable of suppressing electrical oscillation of an LC filter circuit even when the magnitude of a torque command  $T_m^*$  is small or close to zero and thus is capable of stably driving and controlling the AC motor.

**Solution to Problem**

In order to solve the above problems and achieve the object, in the present invention, a control apparatus for an AC motor

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that drives and controls the AC motor via an inverter that includes an LC filter circuit, which includes a reactor and a capacitor, on a DC power supply side and converts a capacitor voltage that is a voltage across the capacitor to an AC voltage at an arbitrary frequency, includes a damping control unit that calculates a damping manipulated variable that suppresses a fluctuation in the capacitor voltage, wherein the damping control unit calculates a fluctuation rate of the capacitor voltage, calculates the damping manipulated variable based on the fluctuation rate and a predetermined value that is set as a value in a predetermined range around a maximum torque of the AC motor, generates a torque command or a current command of the AC motor based on the damping manipulated variable, and controls the inverter so as to change a current flowing in the inverter in a fluctuation suppressing direction with respect to a fluctuation in the capacitor voltage based on the torque command or the current command.

**Advantageous Effects of Invention**

According to the present invention, an effect is obtained where it is possible to suppress electrical oscillation of an LC filter circuit even when the magnitude of a torque command  $T_m^*$  is small or close to zero and thus stably drive and control an AC motor.

**BRIEF DESCRIPTION OF DRAWINGS**

FIG. 1 is a block diagram illustrating an example of a configuration of an AC motor system according to an embodiment.

FIG. 2 is an explanatory diagram illustrating an example of a circuit in which a constant-power-controlled inverter is connected to an LC filter connected to a DC power supply.

FIG. 3 is a diagram illustrating a transfer function block of a system shown in FIG. 2.

FIG. 4 is an explanatory diagram illustrating an example of a circuit in which a load constituted by a resistor is connected to an LC filter connected to a DC power supply.

FIG. 5 is a diagram illustrating a transfer function block of a system shown in FIG. 4.

FIG. 6 is a diagram explaining a relation among signals of respective parts of a damping control unit.

**DESCRIPTION OF EMBODIMENTS**

Exemplary embodiments of a control apparatus for an AC motor according to the present invention will be explained below in detail with reference to the accompanying drawings. The present invention is not limited to the embodiments.

**Embodiment**

FIG. 1 is a block diagram illustrating an example of a configuration of an AC motor system according to the embodiment. As shown in FIG. 1, the AC motor system according to the present embodiment includes a DC power supply 1, an LC filter circuit constituted by a reactor 2 and a capacitor 3 for suppressing a harmonic current from flowing to a power supply side, an inverter 4 that converts a voltage (a capacitor voltage)  $E_{fc}$  across the capacitor 3 to an AC voltage having an arbitrary frequency, an AC motor 6, and a control apparatus 50 for an AC motor that drives and controls the AC motor 6.

The control apparatus 50 for an AC motor is constituted by a vector control unit 30 and a damping control unit 40, and a signal  $\omega_r$  from a speed detector 7 that detects a rotational

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speed of the AC motor 6, signals  $I_u$ ,  $I_v$ , and  $I_w$  from current detectors 5a to 5c that detect motor currents, respectively, and a voltage  $E_{fc}$  across the capacitor 3 are input to the control apparatus 50. In the present embodiment, the AC motor system is configured to include the current detectors for three phases, respectively. Alternatively, it suffices that the AC motor system is configured to include the current detectors for at least two phases, respectively because a current in the remaining phase can be calculated by computation.

A speed sensor-less vector control system for computing and calculating a rotational speed of the AC motor 6 without providing the speed detector 7 is already put into practical use, in which case, it is unnecessary to provide the speed detector 7.

Furthermore, while the AC motor 6 is described below by referring to an example of a configuration that uses an induction motor as the AC motor 6, the damping control unit 40 disclosed in the present invention is also effective for a case of using a synchronous motor as the AC motor 6.

A configuration of the vector control unit 30 is described next. The vector control unit 30 controls the AC motor on a dq-axis rotating coordinate system, where an axis that matches an axis of a secondary magnetic flux of the AC motor 6 is defined as a d-axis and an axis orthogonal to the d-axis is defined as a q-axis. That is, the vector control unit 30 executes what is called a vector control.

The vector control unit 30 is configured such that a torque basic command  $T_{m0}^*$  and a secondary magnetic flux command  $\phi_2^*$  that are generated by a high-level control unit (not shown) and the U-phase current  $I_u$ , the V-phase current  $I_v$ , and the W-phase current  $I_w$  detected by the current detectors 5a to 5c, respectively are input to the vector control unit 30. The vector control unit 30 performs a control such that a torque  $T_m$  generated by the AC motor 6 matches a torque command  $T_m^*$  generated from the torque basic command  $T_{m0}^*$  (a generating method therefor is described later).

Configurations of respective functional blocks in the vector control unit 30 are described next. A q-axis current-command generation unit 8 and a d-axis current-command generation unit 9 compute a d-axis (excitation amount) current command  $I_d^*$  and a q-axis (torque amount) current command  $I_q^*$  from the torque command  $T_m^*$  obtained by adding a damping manipulated variable DAMPCN (described later) to the torque basic command  $T_{m0}^*$  input from an external control unit (not shown), the secondary magnetic flux command  $\phi_2^*$ , and circuit constants of the AC motor 6, as expressed by the following Equations (1) and (2), respectively. In Equations (1) and (2),  $L_2$  indicates a secondary self-inductance of the motor and is expressed as  $L_2 = M + I_2$ .  $M$  indicates a mutual inductance,  $I_2$  indicates a secondary leakage inductance,  $s$  indicates a differential operator,  $PP$  indicates the number of pole pairs of the AC motor 6, and  $R_2$  indicates a secondary resistance of the AC motor 6.

$$I_q^* = (T_m^* / (\phi_2^* \cdot PP)) \cdot (L_2 / M) \quad (1)$$

$$I_d^* = \phi_2^* / M + L_2 / (M \cdot R_2) \cdot s \phi_2^* \quad (2)$$

A slip-angular-frequency-command generation unit 19 computes a slip angular frequency command  $\omega_s^*$  to be supplied to the AC motor 6 from the d-axis current command  $I_d^*$ , the q-axis current command  $I_q^*$ , and the circuit constants of the AC motor 6, as expressed by the following Equation (3).

$$\omega_s^* = (I_q^* / I_d^*) \cdot (R_2 / L_2) \quad (3)$$

An adder 20 adds the slip angular frequency command  $\omega_s^*$  calculated by the Equation (3) to the rotational angular frequency  $\omega_r$  output from the speed detector 7 attached to an

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axial end of the AC motor 6, and outputs an addition result as an inverter angular frequency  $\omega$  to be output from the inverter 4. An integrator 21 integrates the inverter angular frequency  $\omega$  to generate a phase angle  $\theta$  for coordinate conversion, and inputs the phase angle  $\theta$  to a dq-axis-to-three-phase coordinate converter 22 and a three-phase-to-dq-axis coordinate converter 23.

The three-phase-to-dq-axis coordinate converter 23 converts the U-phase current  $I_u$ , the V-phase current  $I_v$ , and the W-phase current  $I_w$  detected by the respective current detectors 5a to 5c to a d-axis current  $I_d$  and a q-axis current  $I_q$  on the dq coordinates calculated by the following Equation (4).

$$\begin{pmatrix} I_q \\ I_d \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos \theta & \cos \left( \theta - \frac{2}{3}\pi \right) & \cos \left( \theta + \frac{2}{3}\pi \right) \\ \sin \theta & \sin \left( \theta - \frac{2}{3}\pi \right) & \sin \left( \theta + \frac{2}{3}\pi \right) \end{pmatrix} \begin{pmatrix} I_u \\ I_v \\ I_w \end{pmatrix} \quad (4)$$

A subtracter 10 subtracts the q-axis current  $I_q$  from the q-axis current command  $I_q^*$  and inputs a subtraction result to a q-axis current controller 12 arranged on a next stage. The q-axis current controller 12 executes a proportional-plus-integral control over the input value and outputs a q-axis voltage compensation value  $q_e$ . A subtracter 11 subtracts the d-axis current  $I_d$  from the d-axis current command  $I_d^*$  and inputs a subtraction result to a d-axis current controller 13 arranged on a next stage. The d-axis current controller 13 performs a proportional-plus-integral amplification on the input value and outputs a d-axis voltage compensation value  $d_e$ .

The q-axis current error  $q_e$  and the d-axis current error  $d_e$  are expressed by the following Equations (5) and (6), respectively.

In the following equations,  $s$  indicates a differential operator,  $K_1$  indicates a proportional gain, and  $K_2$  indicates an integral gain.

$$q_e = (K_1 + K_2 / s) \cdot (I_q^* - I_q) \quad (5)$$

$$d_e = (K_1 + K_2 / s) \cdot (I_d^* - I_d) \quad (6)$$

A voltage-decoupling computation unit 14 computes a d-axis feedforward voltage  $E_d^*$  and a q-axis feedforward voltage  $E_q^*$  from the d-axis current command  $I_d^*$ , the q-axis current command  $I_q^*$ , and the circuit constants of the AC motor 6, as expressed by the following Equations (7) and (8), respectively.

In Equations (7) and (8) described above,  $\sigma$  indicates a leakage coefficient defined as  $\sigma = 1 - M^2 / (L_1 \cdot L_2)$ . Furthermore,  $L_1$  indicates a primary self-inductance of the motor and is calculated as  $L_1 = M + I_1$ .  $L_2$  indicates a secondary self-inductance of the motor and is calculated as  $L_2 = M + I_2$ .  $I_1$  indicates a primary leakage inductance and  $I_2$  indicates a secondary leakage inductance.

$$E_d^* = -\omega \cdot L_1 \cdot \sigma \cdot I_q^* + (M / L_2) \cdot s \phi_2^* \quad (7)$$

$$E_q^* = \omega \cdot L_1 \cdot \sigma \cdot I_d^* + (\omega \cdot M \cdot \phi_2^*) / L_2 \quad (8)$$

An adder 17 is configured to obtain a q-axis voltage command  $V_q^*$  by adding the q-axis voltage compensation value  $q_e$  to the q-axis feedforward voltage  $E_q^*$  and input the q-axis voltage command  $V_q^*$  to the dq-axis-to-three-phase coordinate converter 22. An adder 18 is configured to obtain a d-axis voltage command  $V_d^*$  by adding the d-axis voltage compensation value  $d_e$  to the d-axis feedforward voltage  $E_d^*$  and input the d-axis voltage command  $V_d^*$  to the dq-axis-to-three-phase coordinate converter 22.



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The q-axis voltage command  $Vq^*$  and the d-axis voltage command  $Vd^*$  are expressed by the following Equations (9) and (10), respectively.

$$Vq^* = E_{fc}^* + qe \quad (9)$$

$$Vd^* = E_{dc}^* + de \quad (10)$$

Finally, the dq-axis-to-three-phase coordinate converter **22** generates voltage commands  $Vu^*$ ,  $Vv^*$ , and  $Vw^*$  for the three phases from the q-axis voltage command  $Vq^*$  and the d-axis voltage command  $Vd^*$ , and controls the inverter **4**.

In this way, the vector control unit **30** executes a vector control to which a current feedback control is added so that a q-axis current  $Iq$  and a d-axis current  $Id$ , which are actual currents of the AC motor **6**, match the q-axis current command  $Iq^*$  and the d-axis current command  $Id^*$ , which are calculated from the torque command  $Tm^*$  and the secondary magnetic flux command  $\phi_2^*$ , respectively, whereby the AC motor **6** outputs a torque  $Tm$  matching the torque command  $Tm^*$  and then rotates. The control operation described above is not explained in detail because it is basically identical to a well-known vector control.

A configuration of the damping control unit **40** that is a main part of the present invention is described next. Before starting a specific description of the damping control unit **40** shown in FIG. 1, an explanation is briefly made of the cause of the electrical oscillation of the LC filter circuit and an electrical-oscillation suppression principle of the LC filter circuit that forms the basis of the configuration of the damping control unit shown in the first embodiment of the present invention.

FIG. 2 is a diagram illustrating a circuit in which the constant-power-controlled inverter **4** is connected to the LC filter connected to the DC power supply **1**. FIG. 2 expresses the system shown in FIG. 1 in a simplified manner.

As shown in FIG. 2, the configuration is such that the LC filter circuit constituted by the reactor **2** and the capacitor **3** is connected to the DC power supply **1** and the inverter **4** that drives and controls the AC motor **6** is connected to the capacitor **3**. The reactor **2** is constituted by an inductance part  $L$  and a resistance part  $R$ . An electrostatic capacity of the capacitor **3** is  $C$ .

The inverter **4** is configured to be controlled such that an output from the AC motor **6** is kept constant even if the capacitor voltage  $E_{fc}$  fluctuates, that is, a constant power characteristic is obtained with respect to a fluctuation in the capacitance voltage  $E_{fc}$ . That is, the inverter **4** is controlled such that an input power  $P_{inv}$  input to the inverter **4** does not change even if the  $E_{fc}$  fluctuates.

In the system shown in FIG. 2 configured as described above, the inverter **4** viewed from a side of the DC power supply **1** has a negative resistance characteristic. The negative resistance characteristic refers to a characteristic that an inverter input current  $I_{dc}$  decreases as the capacitor voltage  $E_{fc}$  increases and that the inverter input current  $I_{dc}$  increases as the capacitor voltage  $E_{fc}$  decreases. The negative resistance characteristic is opposite to a normal resistance (a positive resistance) in a current change relative to a voltage change. It is known as common knowledge that the normal resistance (the positive resistance) is that a current increases as a voltage increases and that a current decreases as a voltage decreases.

As described above, a DC part of the system shown in FIG. 2 exhibits the negative resistance characteristic and operates to accelerate increasing the capacitor voltage  $E_{fc}$  because the inverter input current  $I_{dc}$  decreases as the capacitor voltage  $E_{fc}$  increases. Conversely, the DC part operates to accelerate

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decreasing the capacitor voltage  $E_{fc}$  because the inverter input current  $I_{dc}$  increases as the capacitor voltage  $E_{fc}$  decreases. Accordingly, the system is unable to damp the fluctuation in the capacitor voltage  $E_{fc}$ , with the result that the electrical oscillation of the LC filter circuit expands and that the capacitor voltage  $E_{fc}$  keeps oscillating at a frequency near a resonance frequency of the LC filter. The above description is a qualitative explanation.

Next, the phenomenon described above is described quantitatively by obtaining and evaluating a transfer function of the system shown in FIG. 2. First, a transfer function from a DC voltage  $E_s$  to the capacitor voltage  $E_{fc}$  is obtained from the system shown in FIG. 2.

As described above, the inverter **4** is controlled to have a constant output. In this case, a relational expression among the inverter input power  $P_{inv}$ , the capacitor voltage  $E_{fc}$ , and the inverter input current  $I_{dc}$  is expressed by the following Equation (11).

$$E_{fc} \cdot I_{dc} = P_{inv} (= \text{constant}) \quad (11)$$

The above relation is nonlinear, so that the relation is linearized. Assuming that operating points in that case are  $E_{fc0}$  and  $I_{dc0}$ , the following Equation (12) is established near the operating points.

$$I_{dc} = -\frac{P_{inv} \cdot (E_{fc} - E_{fc0})}{E_{fc0}^2} + I_{dc0} \quad (12)$$

From FIG. 2 and the Equation (12), a block diagram of the transfer function of the system shown in FIG. 2 becomes as shown in FIG. 3. From the block diagram of the transfer function shown in FIG. 3, a closed-loop transfer function  $G(s)$  from the DC voltage  $E_s$  to the capacitor voltage  $E_{fc}$  is expressed by the following Equation (13).

$$G(s) = \frac{1}{C \cdot L} \cdot \frac{1}{s^2 + \left(\frac{R}{L} - \frac{P_{inv}}{C \cdot E_{fc0}^2}\right) \cdot s - \frac{1}{C \cdot L} \left(\frac{R \cdot P_{inv}}{E_{fc0}^2} - 1\right)} \quad (13)$$

To ensure that this transfer function  $G(s)$  is stable, it is necessary for all poles of the  $G(s)$  to be negative. That is, it is necessary that solutions of a characteristic equation shown in the following Equation (14) that is a denominator of the  $G(s)$  are all negative.

$$s^2 + \left(\frac{R}{L} - \frac{P_{inv}}{C \cdot E_{fc0}^2}\right) \cdot s - \frac{1}{C \cdot L} \left(\frac{R \cdot P_{inv}}{E_{fc0}^2} - 1\right) = 0 \quad (14)$$

Assuming that the solutions of the above equation are  $\alpha$  and  $\beta$ , it is necessary that the both are negative. Therefore, as conditions for making the  $G(s)$  stable, it is possible to derive the following Equations (15) and (16). The following Equations (15) and (16) can be derived from a relation between the solutions and coefficients.

$$\alpha + \beta = -\left(\frac{R}{L} - \frac{P_{inv}}{C \cdot E_{fc0}^2}\right) < 0 \quad (15)$$

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-continued

$$\alpha \cdot \beta = -\frac{1}{C \cdot L} \left( \frac{R \cdot P_{inv}}{E_{fc0}^2} - 1 \right) > 0 \quad (16)$$

The Equation (16) is ignored here because it does not include useful information. The Equation (15) is rewritten into the following Equation (17).

$$R > \frac{L}{C} \cdot \frac{P_{inv}}{E_{fc0}^2} \quad (17)$$

The Equation (17) indicates that the R necessary to stabilize the system can be low as the L is smaller, the C is greater, the P<sub>inv</sub> is lower, and the E<sub>fc0</sub> is higher. For example, when conditions of L=12 mH, C=6600 μF, P<sub>inv</sub>=1000 KW, and E<sub>fc0</sub>=1500 V that are general values in an inverter system for driving an electric vehicle are assigned to the Equation (17), a value of the R that can stabilize the system is R>0.8 (Ω).

However, because a resistance component present on the DC side is generally as very low as about several tens of mΩ, it is difficult to satisfy the Equation (17). Accordingly, the system becomes unstable and oscillation occurs in the LC filter circuit. That is, it can be understood that the capacitor voltage E<sub>fc</sub> oscillates and diverges unless a resistor satisfying the Equation (17) is added to the circuit shown in FIG. 2 or the system is controlled to become stable.

In practice, the addition of the resistor makes the apparatus large in size and increases loss. Therefore, it is necessary to adopt a method of controlling the system and a specific conventional method is as disclosed in Patent Literature 1.

A case where a load is a resistance (a normal positive resistance) load is described quantitatively similarly to the above. FIG. 4 is a diagram illustrating a circuit in which a load constituted by a resistor 60 is connected to the LC filter connected to the DC power supply 1. As compared with the circuit shown in FIG. 2, the circuit shown in FIG. 4 is such that the inverter 4 and the AC motor 6 are replaced by the resistor 60. A resistance value of the resistor 60 is defined as R<sub>0</sub>.

A block diagram of a transfer function of the system shown in FIG. 4 is as shown in FIG. 5. From FIG. 5, a closed-loop transfer function G<sub>p</sub>(s) from the voltage E<sub>s</sub> of the DC power supply 1 to the capacitor voltage E<sub>fc</sub> is expressed by the following Equation (18).

$$G_p(s) = \frac{\frac{1}{C \cdot L}}{s^2 + \left( \frac{1}{C \cdot R_0} + \frac{R}{L} \right) \cdot s + \frac{1}{C \cdot L} \cdot \left( \frac{R}{R_0} + 1 \right)} \quad (18)$$

A characteristic equation of the closed-loop transfer function G<sub>p</sub>(s) expressed by the Equation (18) is expressed by the following Equation (19).

$$s^2 + \left( \frac{1}{C \cdot R_0} + \frac{R}{L} \right) \cdot s + \frac{1}{C \cdot L} \cdot \left( \frac{R}{R_0} + 1 \right) = 0 \quad (19)$$

Because of R>0, the conditions that solutions of the characteristic equation expressed by the Equation (19) are all negative are always satisfied. This indicates that the case where the load is constituted by the resistor 60 ensures that the system is always stable.

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In FIG. 4, when the resistance R of the reactor 2 is ignored, it is impossible to suppress the oscillation and the system reaches a stability limit because of no power loss in the system when the resistance value of the resistor 60 is zero.

Accordingly, once oscillation occurs due to a disturbance such as a fluctuation in the power supply voltage, it is impossible to suppress the oscillation and the LC filter circuit keeps oscillating. Furthermore, it is known that the system becomes more stable as the resistance value of the resistor 60 is lower, that is, the power (a positive resistance component) consumed by the resistor 60 is higher.

As described above, it is understood that the circuit in which the resistor 60 is connected to the LC filter connected to the DC power supply 1 is always stable. The present invention pays attention to this principle and is characterized in that the inverter 4 is controlled such that the inverter 4 has a characteristic equivalent to a characteristic exhibited in a case of connecting the resistor 60 to the LC filter circuit with respect to an oscillation component of the capacitor voltage E<sub>fc</sub>.

A characteristic of the circuit in which the resistor 60 is connected to an output of the LC filter shown in FIG. 4 is described below. In the circuit of FIG. 4, assuming that the current I<sub>dc</sub> flows to the resistor 60 at the capacitor voltage E<sub>fc</sub>, power PR consumed by the resistor 60 is expressed by the following Equation (20).

$$PR = E_{fc} \cdot I_{dc} \quad (20)$$

When the capacitor voltage E<sub>fc</sub> fluctuates to increase to n times as high as an initial value, the current I<sub>dc</sub> flowing to the resistor 60 similarly becomes n times as high as an initial value. Therefore, the power PR<sub>n</sub> consumed by the resistor 60 at this time is expressed by the following Equation (21).

$$PR_n = n \cdot E_{fc} \cdot n \cdot I_{dc} = n^2 \cdot E_{fc} \cdot I_{dc} = n^2 \cdot PR \quad (21)$$

That is, it is found that the power PR<sub>n</sub> consumed by the resistor 60 is proportional to the square of a change rate of the capacitor voltage E<sub>fc</sub>.

This indicates that the inverter 4 can be operated to have a positive resistance characteristic with respect to the fluctuation in the capacitor voltage E<sub>fc</sub> by controlling the inverter 4 to satisfy the relation of the Equation (21).

The output from the AC motor 6 is expressed by (a rotational frequency FM of the AC motor 6) × (the output torque T<sub>m</sub>) and, when loss is ignored, this is equal to the input power P<sub>inv</sub> of the inverter 4. Therefore, the following Equation (22) is established.

$$P_{inv} = FM \cdot T_m \quad (22)$$

To control the inverter 4 to operate to have a positive resistance characteristic with respect to the fluctuation in the capacitor voltage E<sub>fc</sub>, it suffices that power P<sub>invn</sub> in a case where the capacitor voltage E<sub>fc</sub> is n times as high as the initial value satisfies the relation of the following Equation (23) similarly to the Equation (21).

$$P_{invn} = n^2 \cdot P_{inv} = n^2 \cdot FM \cdot T_m \quad (23)$$

In this Equation, the rotational frequency FM of the AC motor 6 is a value that changes depending on the speed of an electric vehicle. On the other hand, the resonance frequency of the LC filter circuit dealt with by the damping control unit 40 is 10 Hz to 20 Hz and converted to a cycle of 50 ms to 100 ms in time. Consequently, it can be considered that an oscillation cycle of the LC filter circuit is sufficiently short as compared with a change in the speed of the electric vehicle. Therefore, in the case of considering the configuration of the

damping control unit 40, it can be assumed that the rotational frequency FM of the AC motor 6 is constant.

Therefore, the inverter input power P<sub>inv</sub> can be changed proportionally to the square of the change rate of the capacitor voltage E<sub>fc</sub> by controlling the inverter 4 so as to multiply the torque T<sub>m</sub> of the AC motor 6 by n<sup>2</sup> when the capacitor voltage E<sub>fc</sub> becomes n times as high as the initial value. With this configuration, it is possible for the inverter 4 to have a positive resistance characteristic with respect to the fluctuation amount in the capacitor voltage E<sub>fc</sub>, to suppress the electrical oscillation of the LC filter circuit, and to stabilize the system.

Therefore, from the Equations (22) and (23), a change amount ΔP of the inverter input power to be added for the stabilization in the case where the capacitor voltage E<sub>fc</sub> becomes n times as high as the initial value at the torque command of T<sub>m</sub>\* can be expressed by the following Equation (24).

$$\Delta P = P_{invn} - P_{inv} = n^2 \cdot FM \cdot T_m^* - FM \cdot T_m^* \quad (24)$$

A torque-command change amount ΔT<sub>m</sub>\* to be added that is necessary to obtain the change amount ΔP of the inverter input power expressed by the Equation (24) is expressed by the following Equation (25).

$$\Delta T_m^* = \Delta P / FM = (n^2 - 1) \cdot T_m^* \quad (25)$$

Consequently, the inverter 4 can be made to have a positive resistance characteristic and the system can be stabilized by controlling the inverter 4 by adding the torque-command change amount ΔT<sub>m</sub>\* to the torque command T<sub>m</sub>\*. However, because a positive resistance amount decreases as the torque command T<sub>m</sub>\* is smaller, an effect of suppressing the oscillation of the capacitor voltage E<sub>fc</sub> is decreased in a case where the torque command T<sub>m</sub>\* is small as compared with a case where the torque command T<sub>m</sub>\* is sufficiently large (for example, a case where the torque command T<sub>m</sub>\* is a rated torque or a maximum torque).

For example, when the torque command T<sub>m</sub>\* is zero or a value close to zero, the ΔT<sub>m</sub>\* (that is, ΔP) becomes zero or a value close to zero based on the Equation (25). As a result, the inverter input power P<sub>inv</sub> cannot be changed. Accordingly, it is difficult to suppress the electrical oscillation in a case where the electrical oscillation of the capacitor voltage E<sub>fc</sub> occurs due to an external factor such as a fluctuation in an overhead line voltage.

In the present embodiment, the configuration is such that even when the torque command T<sub>m</sub>\* is zero, it is possible to obtain a change amount ΔP<sub>a</sub> of the inverter input power similar to that in a case where the torque command T<sub>m</sub>\* is a value equal to or larger than a certain level (T<sub>m</sub>\*=T<sub>ma</sub>).

From the Equations (24) and (25), the change amount ΔP<sub>a</sub> of the inverter input power to be added for the stabilization in the case where the capacitor voltage E<sub>fc</sub> becomes n times as high as the initial value at the torque command of T<sub>m</sub>\*=T<sub>ma</sub> can be expressed by the following Equation (26).

$$\Delta P_a = P_{invn} - P_{inv} = n^2 \cdot FM \cdot T_{ma} - FM \cdot T_{ma} \quad (26)$$

A torque-command change amount ΔT<sub>ma</sub>\* to be added, necessary to obtain the change amount ΔP<sub>a</sub> of the inverter input power expressed by the Equation (26) is expressed by the following Equation (27).

$$\Delta T_{ma}^* = \Delta P_a / FM = (n^2 - 1) \cdot T_{ma} \quad (27)$$

Consequently, it is possible to obtain the change amount ΔP<sub>a</sub> of the inverter input power similar to that in a case where the torque command T<sub>m</sub>\* is a value equal to or larger than a certain level (T<sub>m</sub>\*=T<sub>ma</sub>) with respect to the fluctuation in the capacitor voltage E<sub>fc</sub> irrespective of the magnitude of the

torque command T<sub>m</sub>\* by controlling the inverter 4 while adding the torque command change amount ΔT<sub>ma</sub>\* to the torque command T<sub>m</sub>\*. With this configuration, it is possible to suppress the electrical oscillation even when the electrical oscillation of the capacitor voltage E<sub>fc</sub> occurs due to the external factor such as a fluctuation in the overhead line voltage at the time the torque command T<sub>m</sub>\* is equal to or close to zero.

The value T<sub>ma</sub> used in the Equation (27) and the like is preferably set to a value corresponding to a value closer to the maximum torque of the AC motor 6 that is a control target. For example, it suffices to set the value T<sub>ma</sub> to the maximum torque of the AC motor 6 or a large value equal to or smaller than the maximum torque (such as a rated torque (generally equal to or higher than 50% of the maximum torque) or a starting torque (generally equal to the maximum torque)). When the maximum torque of the AC motor 6 is, for example, 1500 Nm, the value T<sub>ma</sub> is preferably set to 1500 or a value that is as large as possible and smaller than 1500. A small value T<sub>ma</sub> is not preferable because the effect of suppressing the electrical oscillation is decreased as can be understood from the above explanation. When the value T<sub>ma</sub> is far larger than the maximum torque of the AC motor 6 (equal to or larger than 200% of the maximum torque, for example), the change amount of the torque command T<sub>m</sub>\* becomes extremely large, resulting in an unstable operation. The value T<sub>ma</sub> may be set larger than the maximum torque in a range in which the value T<sub>ma</sub> is not far larger than the maximum torque. According to a result of a simulation conducted by the inventor, the value T<sub>ma</sub> preferably falls in the range from 50% to 200% of the maximum torque of the AC motor 6.

A specific configuration of the method described above is described next with reference to FIGS. 1 and 6. FIG. 6 is a diagram explaining a relation among signals within the damping control unit 40 according to the first embodiment of the present invention.

The voltage E<sub>fc</sub> across the capacitor 3 is input to the damping control unit 40 and branched off into two systems therein. On one hand, a high-pass filter (hereinafter, an "HPF") 41 and a low-pass filter (hereinafter, an "LPF") 43 cut off unnecessary high frequency components and unnecessary low frequency components, and calculate an oscillation component E<sub>fca</sub> that is only a component extracted near the resonance frequency of the LC filter circuit. For example, when the capacitor voltage E<sub>fc</sub> oscillates around 1500 V from 1650 V to 1350 V as shown in FIG. 6(a), the E<sub>fca</sub> is the signal that fluctuates in the same phase as that of the oscillation component of the capacitor voltage E<sub>fc</sub> in a range from +150 V to -150 V as shown in FIG. 6(b).

On the other hand, an LPF 42 extracts only a DC component as a DC component E<sub>fcd</sub>. The HPF 41, the LPF 42, and the LPF 43 are primary filters constituted by first order lag elements, and a configuration of each of which is not described here because the configuration is well known. Obviously, although second or higher order filters may be used, the configurations of the filters become complicated.

Mechanisms of the HPF 41 and the LPF 43 are described. The reason for the need of the LPF 43 is to remove the high frequency components that are contained in the capacitor voltage E<sub>fc</sub> and become a disturbance to the control system. However, a lower limit of the high frequency components to be removed is several hundred Hz and is close to a resonance frequency band (generally about 10 to 20 Hz) of the LC filter that is a damping control target. Accordingly, when the high frequency components are removed using only the LPF 43, even resonance frequency components of the LC filter con-

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tained in the oscillation component E<sub>fca</sub> are affected and a phase lag is caused in the resonance frequency components, which is not preferable.

The HPF 41 is additionally connected to the LPF 43 in series and a filter is configured by a combination of the HPF 41 and the LPF 43. This can improve the phase lag in the resonance frequency components of the LC filter contained in the oscillation component E<sub>fca</sub> while ensuring a similar high-frequency-component removal characteristic to that in a case of using the LPF 43 solely. It is desirable that characteristics of the HPF 41 and the LPF 43 are such that a frequency at which a gain becomes one is made to match the resonance frequency (10 Hz to 20 Hz) of the LC filter circuit.

An adder 44 adds the DC component E<sub>fcd</sub> to the oscillation component E<sub>fca</sub> calculated as described above and an addition result is defined as a filtered capacitor voltage E<sub>fcd</sub> (FIG. 6(e)). Further, a divider 45 divides the filtered capacitor voltage E<sub>fcd</sub> by the DC component E<sub>fcd</sub>, thereby calculating a fluctuation rate E<sub>fcdp</sub> of the capacitor voltage E<sub>fc</sub>. The E<sub>fcdp</sub> is input to a square computation unit 48.

The square computation unit 48 squares the fluctuation rate E<sub>fcdp</sub> of the capacitor voltage E<sub>fc</sub> and outputs a calculation result to a multiplier 49 as a signal DM1. The multiplier 49 multiplies the signal DM1 by the value T<sub>ma</sub> and outputs a signal DM2 that is a multiplication result to a subtracter 46. The subtracter 46 subtracts the value T<sub>ma</sub> from the signal DM2 and outputs a subtraction result to the vector control unit 30 as the damping manipulated variable DAMPCN (FIG. 6(e)). Finally, an adder 24 of the vector control unit 30 adds the damping manipulated variable DAMPCN to the torque basic command T<sub>m0</sub>\*, and the vector control unit 30 executes the vector control using the torque command T<sub>m</sub>\* that is an addition result.

By executing a vector control using the torque command T<sub>m</sub>\* generated as described above, the inverter 4 can be controlled to operate to have a positive resistance characteristic with respect to the fluctuation in the capacitor voltage E<sub>fc</sub> and the oscillation of the capacitor voltage E<sub>fc</sub> can be suppressed. Furthermore, it is possible to obtain the change amount ΔP<sub>a</sub> of the inverter input power similar to that in a case where the torque command T<sub>m</sub>\* is a value equal to or larger than a certain level (T<sub>m</sub>\*=T<sub>ma</sub>) with respect to the fluctuation in the capacitor voltage E<sub>fc</sub> irrespective of the magnitude of the torque command T<sub>m</sub>\*. Accordingly, even in a case where an electrical oscillation of the capacitor voltage E<sub>fc</sub> occurs due to an external factor such as a fluctuation in the overhead line voltage at the torque command T<sub>m</sub>\* that is either equal to zero or a small value, it is possible to suppress the electrical oscillation. Therefore, it is possible to suppress the electrical oscillation of the LC filter circuit and to ensure that the AC motor 6 operates stably.

As described above, according to the present embodiment, the damping control unit that automatically calculates an optimum damping manipulated variable DAMPCN and dispenses with gain settings can be configured. Furthermore, because the constants of the AC motor 6 are not used in the calculation of the damping manipulated variable DAMPCN, there is no need to adjust the control system even when the type of the AC motor 6 changes.

An example of a case of using the induction motor as the AC motor 6 has been explained above. However, the configuration of the damping control unit and a method of calculating the damping manipulated variable described above can be also applied to the vector control unit in a case of using the above motor or another AC motor.

In the configuration according to the present embodiment, the damping manipulated variable DAMPCN is added to the

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torque basic command T<sub>m0</sub>\*. Alternatively, even when the damping manipulated variable DAMPCN is added to the q-axis current command I<sub>q</sub>\* synonymous with the torque command, similar effects can be obtained. In a case of adding the DAMPCN to the q-axis current command I<sub>q</sub>\*, it is necessary to convert a torque command-based value to a q-axis current command-based value using the Equation (1) before the addition.

Specifically, it suffices that DAMPCNIQ is calculated from the DAMPCN as expressed by the following Equation (28) and is added to the q-axis current command I<sub>q</sub>\*, and that an addition result is configured as a new q-axis current command I<sub>q</sub>\*.

$$\text{DAMPCNIQ} = (\text{DAMPCN} / (\phi^2 \cdot PP)) \cdot (L2/M) \quad (28)$$

In the configuration according to the present invention, there is no need to switch the damping manipulated variable during power running and regenerative running of the AC motor 6, thereby making it possible to simplify the control system.

Furthermore, in the configuration according to the present invention, it is only the value T<sub>ma</sub> that is a set value necessary in a process of calculating the damping manipulated variable as described above. The value T<sub>ma</sub> is a value that can be easily grasped from specifications of the AC motor 6 to be used. Therefore, there is no need to derive setting gains or the like for a simulation or an actual object adjustment operation at the time of designing the damping control, thereby making it possible to simplify an adjustment operation of the control system.

The configuration described in the above embodiment is only an example of the contents of the present invention. The configuration can be combined with other well-known techniques, and it is obvious that the present invention can be configured while modifying it without departing from the scope of the invention, such as omitting a part of the configuration.

Furthermore, the present invention is not limited to a control apparatus for an AC motor for electrical railroads, and it is obvious that the present invention is applicable to various related fields.

## REFERENCE SIGNS LIST

- 1 DC power supply
- 2 reactor
- 3 capacitor
- 4 inverter
- 5a to 5c current detector
- 6 AC motor
- 7 speed detector
- 8 q-axis current-command generation unit
- 9 d-axis current-command generation unit
- 10, 11 subtracter
- 12 q-axis current controller
- 13 d-axis current controller
- 14 voltage-decoupling computation unit
- 17, 18 adder
- 19 slip-angular-frequency-command generation unit
- 20 adder
- 21 integrator
- 22 dq-axis-to-three-phase coordinate converter
- 23 three-phase-to-dq-axis coordinate converter
- 24 adder
- 30 vector control unit
- 40 damping control unit
- 41 high-pass filter

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- 42 low-pass filter
- 43 low-pass filter
- 44 adder
- 45 divider
- 46 subtracter
- 48 square computation unit
- 49 multiplier
- 50 control apparatus for AC motor
- 60 resistor

The invention claimed is:

1. A control apparatus for an AC motor that drives and controls the AC motor via an inverter that includes an LC filter circuit, which includes a reactor and a capacitor, on a DC power supply side and converts a capacitor voltage to an AC voltage, the apparatus comprising a damping control unit that calculates a fluctuation rate of the capacitor voltage and calculates a damping manipulated variable that suppresses a fluctuation in the capacitor voltage based on a value obtained by subtracting a preset predetermined value from a product of a signal that is a square of the fluctuation rate and the predetermined value, wherein

a torque command or a current command of the AC motor is generated based on the damping manipulated variable, and the inverter is controlled based on the torque command or the current command.

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2. The control apparatus for an AC motor according to claim 1, wherein the predetermined value is selected in a range from 50% to 200% of the maximum torque of the AC motor.

3. The control apparatus for an AC motor according to claim 1, wherein the predetermined value is the maximum torque of the AC motor.

4. The control apparatus for an AC motor according to claim 1, wherein the predetermined value is a rated torque of the AC motor.

5. The control apparatus for an AC motor according to claim 1, wherein the damping control unit calculates the fluctuation rate of the capacitor voltage by dividing the input capacitor voltage by a DC component contained in the capacitor voltage.

6. The control apparatus for an AC motor according to claim 1, wherein the damping control unit calculates the fluctuation rate of the capacitor voltage by dividing a signal obtained by adding a signal obtained by cutting off an unnecessary high frequency component contained in the capacitor voltage to a DC component contained in the capacitor voltage by the DC component contained in the capacitor voltage.

7. The control apparatus for an AC motor according to claim 1, wherein the preset predetermined value is a value in a predetermined range around a maximum torque of the AC motor.

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